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INVESTIGATION OF SELF-CONTAMINATION OF ELECTROHYDRAULIC COMPACT DRIVES

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Abstract. Self-contained electrohydraulic compact drives with hermetically sealed circuits are a recent trend in industrial hydraulics. For reasons of installation space and costs there are efforts to design these drives without filter. Even if the initial and external contamination is low, the hydraulic circuit contaminates itself with wear particles. This paper focuses on self-contamination of electrohydraulic compact drives, which is investigated by means of endurance tests. The results of a first test series are presented, including the development of particle concentration and wear elements. A visual inspection of the pump provides information on potential wear points. The results presented provide a first insight into the self-contamination process of electrohydraulic compact drives without filter.

Keywords: Electrohydraulic compact drive, EHA, wear, solid contamination, endurance test

INTRODUCTION

Self-contained electrohydraulic compact drives with small, hermetically sealed oil circuits, also known as electro-hydrostatic actuators (EHA), are a recent trend in industrial hydraulics. This is reflected in a number of commercial products, which have emerged on the market in recent years [1, 2, 3, 4, 5, 6]. Equipped with a speed variable pump this drive concept offers a good efficiency (power on demand), a compact design (integrated components, small amount of oil) and user friendliness ("plug and run"). These features are combined with inherently beneficial characteristics of hydraulic drives, such as reliability, high force and good overload protection.

An issue of high interest is the wear behavior of electrohydraulic compact drives performing industrial working cycles. In order to keep maintenance effort and costs low, a longtime filling of oil is aimed at. Since the oil circuit is small, the stress on the pressure fluid rises significantly. This includes oil contamination, mechanical and thermal stress. However, for reasons of installation space and costs there are efforts to build these drives without filter.

Contaminated oil is a main wear and failure cause in hydraulic systems. As statistics demonstrate, up to 80 % of the repair works, maintenance works and failures occurring in hydraulic systems can be traced back to an inadequate condition of the pressure fluid [7]. Main reason for premature failure is mechanical wear caused by an excessive solid content in the oil [8]. For this reason contamination must not exceed permitted limits set by the components manufacturers. The consequences of solid contamination on the wear of hydraulic components is investigated in several publications, i.e. in [9, 10, 11, 12]. Rühlicke [13] and Neubert [14] examined the wear behavior of speed variable pumps with uncontaminated oil. According to Winner [7] and Eckardt [9] solid contamination can be classified into three categories:

- Initial contamination: contamination as a result of incorrect assembly and commissioning, component change, maintenance or oil change (i.e. metal chips, molding sand and scale),
- External contamination: contamination from the environment, infiltrated mainly via the air filter and the rod sealing system (i.e. dirt and atmospheric dust),
- Contamination during operation (self-contamination): contamination through wear and oil aging (i.e. oil aging products, metal and sealing abrasion particles, rust, small filter and hose parts).

Since electrohydraulic compact drives are ready-to-use units, manufacturers are able to ensure a correct assembly and filling. Thus, initial contamination can be reduced to a minimum. Due to the hermetically sealed circuit of hydraulic compact drives the rod sealing system is the only way for external contamination to enter the hydraulic system. Lawrence [10] studied the dust infiltration of rod seals in a dusty environment comparable to agricultural machinery. Nevertheless, the dirt infiltration of rod seals and wipers in industrial environments with lower dirt and dust load, like for example in production halls, is not well known yet. In case of a high external contamination, a bellow can be installed additionally to protect the rod from dust.

Even if the initial and external contamination is low, self-contamination caused by the wear of components cannot be avoided. It is known that in particular during the commissioning process hydraulic pumps show increased abrasion. If these particles remain in the circuit, a self-amplifying wear process may be initialized, which leads to an ongoing deterioration of the pump and the seals. It is not sufficiently well known yet, how

self-contamination develops in small, hermetically sealed circuits without filter and which consequences it has on the wear of components, especially on the pump as one of the most sensitive elements. In order to evaluate whether a design without filter is possible, two aspects have to be examined: firstly, how self-contamination of hydraulic compact drives develops and secondly, how much dust infiltrates in hydraulic systems via modern rod sealing systems in industrial environments like production halls.
This paper focuses on the investigation of self-contamination of self-contained, hermetically sealed hydraulic compact drives without filter. The approach is to analyze this aspect experimentally by means of endurance tests. In chapter 2 the test rig set-up and the testing procedure are introduced, experimental results of a first test series are presented in chapter 3. Finally, a conclusion and an outlook on future works is given in chapter 4.

TEST PROCEDURE AND TEST-RIG SET UP

For the investigation of the self-contamination of electrohydraulic compact drives the test procedure according to **Figure 1** was applied. After defining a representing load cycle, an endurance test was carried out, which was executed by a compact drive demonstrator. Several analyzing methods were applied to receive information on the wear process. Oil samples were taken periodically and analyzed in terms of oil condition and contamination. This includes, inter alia, the analysis of wear elements and particle number. The oil samples were taken at the beginning, at 1/4-, 1/2-, 3/4-way stage and at the end of the endurance test and were analyzed by a commercial oil analyzing company. Additionally, a visual inspection of the pump was carried out to identify potential wear points and damages. With the variation of test parameters in further endurance tests these measures are intended to provide information on the quantity of self-contamination, influences on self-contamination and the impact on the wear of the pumps.

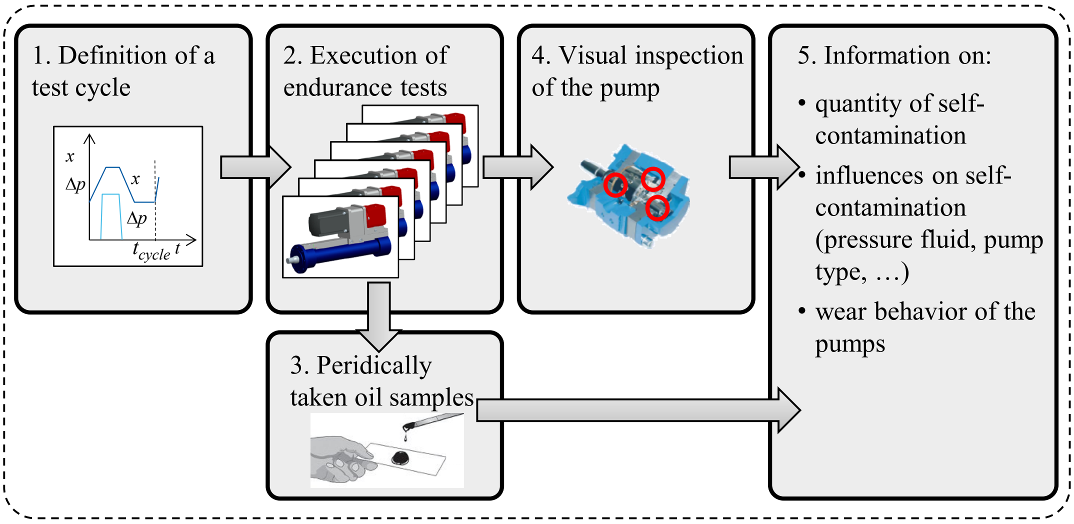


FIGURE 1. Flow chart of the test procedure to investigate self-contamination of electrohydraulic compact drives

The test-rig set-up is illustrated in **Figure 2**. The compact drive demonstrator consists of a single rod cylinder, which is driven by a speed controlled tandem pump. For the first test series, the tandem pump was of internal gear pump type without gap compensation. In order to avoid high pressure peaks and cavitation during the motion, the displacement ratio of the pumps and the piston area ratio of the cylinder match very closely. Additionally, anti-cavitation valves and pressure relief valves are installed. The misbalancing volume of the cylinder is stored in a membrane accumulator. Depending on the position of the piston, the accumulator pressure p_{acc} ranges between 1 and 5 bar. The electric drive consists of a BLDC motor driven by a frequency converter. Several sensors are installed to observe the proper operation of the system. In detail, these are pressure sensors on the piston, rod and low-pressure side, a position sensor measuring the rod position, a motor shaft speed encoder and a temperature sensor on the low pressure side. Furthermore, the motor torque determined by the frequency converter that measures the motor current is captured. For the oil sampling a MINIMESS coupling is installed, which is located on the low pressure side. Before the endurance test was executed a cleaning process of the demonstrator was carried out.

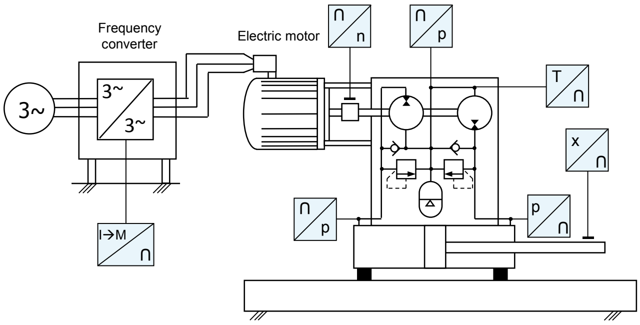


FIGURE 2. Endurance test-rig set-up

As test cycle an industry-oriented load cycle was applied, which relates to a closing/ clamping process of an industrial machine and is illustrated in **Figure 3**. It comprises a load holding, a reversing and a maximum speed phase. In these phases the pump is exposed to several critical operating points. During the load holding phase the pump operates with high load and low speed to compensate leakage. The consequence is a high load on the pump's tribological systems in mixed friction areas. The pressure build-up during the load holding phase is achieved by pushing the piston against the cylinder end stops, whereby the load holding pressure is 70 percent of the nominal pressure of the pump. During the reversing phase alternating stress on the pump drive and zero crossing of the shaft speed is provoked. Two reversing procedures are executed per reversing phase. During the maximum speed phase a high relative speed between shaft and rotary shaft seal, which is pressurized with the accumulator pressure, occurs. The reversing and the maximum speed phases were realized without external loads.

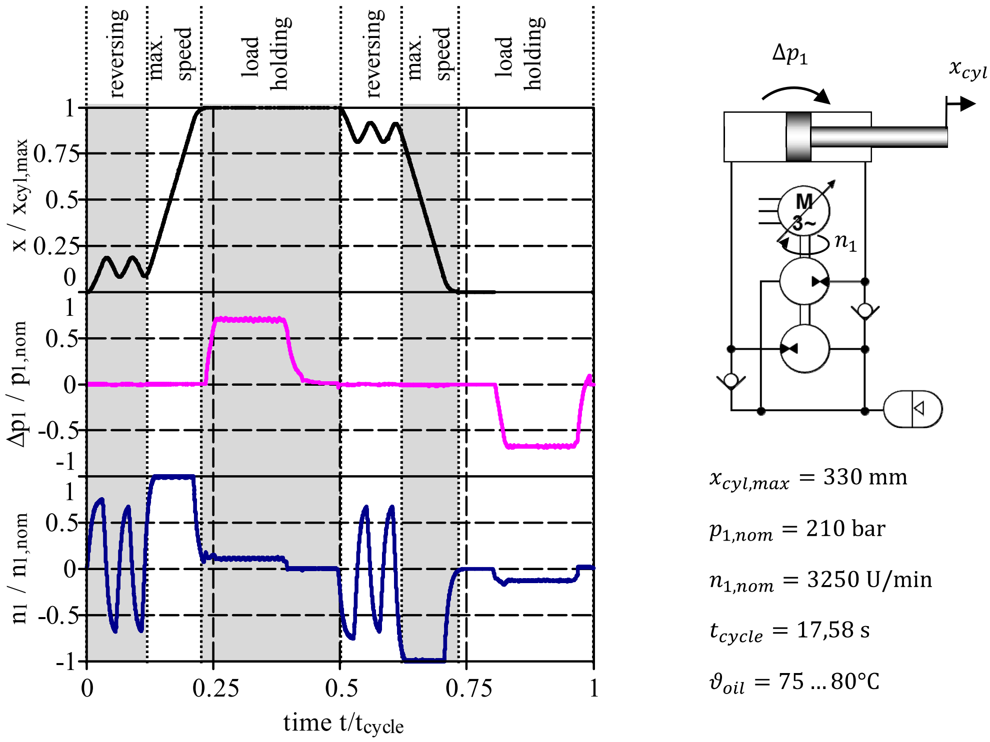


FIGURE 3. Load cycle

With a test duration of 40 days (960 operating hours) and a cycle time of 17.5 seconds approx. 197,000 load cycles were completed. The length of the load holding phase was chosen in a manner that the steady-state temperature of the oil settled between 75 and 80°C. 80°C marks the upper temperature level, which is approved by the pump and cylinder manufacturers.

RESULTS

The results of a first test series are presented in this chapter. In this test series the demonstrator was equipped with a standard hydraulic oil HLP 46 (ISO VG 46). Firstly, the results of the oil analysis are shown. The graph in **Figure 4** illustrates the different metallic wear elements, which were detected in the oil samples. These elements were identified by atomic emission spectroscopy, which detects particles smaller than 5 µm. At the beginning of the experiment a significant increase of iron content can be recognized. In the further course iron content is still increasing, but with a lower rate of increase. Wear elements like tin, copper and lead, which are typical for plain bearing materials, are already present at the beginning and have to be regarded as initial contamination. The source of this contamination could not be clarified finally, an emergence during the cleaning process of the demonstrator has to be taken into account. Nevertheless, it can be seen that the content of these elements remains on a constant level with deviations in a small range. It can be concluded that the conditions during the experiment do not lead to a further abrasion of bearing materials.

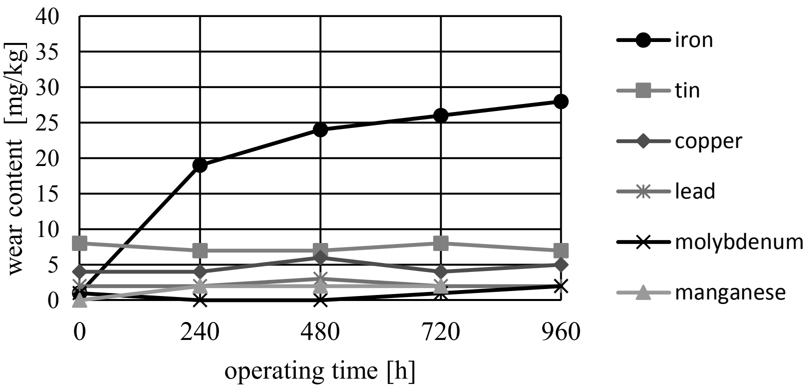


FIGURE 4. Development of wear elements during the endurance test

Graph (a) in **Figure 5** shows the development of the particle concentration (particle numbers) during the endurance test as a function of time. At the beginning of the test the purity class according to ISO 4406 (1999) [15] is 16/14/10. Already between the beginning and 1/4-way stage the purity class rises to 24/22/14. This particle concentration is significantly above the limit of 20/18/15 that is authorized by the pump manufacturer. The strong increase of particles may be led back to a run-in behavior of the pumps, which is known to occur in the first hours or days of commissioning. The external contamination can be assumed to be low, since the drive operates in the laboratory. This is underpinned by the fact that in the further course of the experiment the number of particles does not increase anymore – even a slight decrease of particles smaller than 38 µm can be observed. A fine grinding or a sinking of particles to the accumulator ground can be considered. Particles bigger than 70 µm were not detected during the whole experiment. The difference between the particle concentration at the beginning, at quarter stage and at the end of the endurance test visualizes graph (b) in Figure 5. The particle development shows that with the use of the standard hydraulic oil HLP 46 an excessive contamination of the circuit occurs, which exceeds the given contamination limits of the components significantly. It can be concluded that the operation of an electrohydraulic compact drive realized without filter and equipped with standard hydraulic oil is not to be recommended.

It has to be noted that due to the small amount of oil in the system no extensive flushing was possible before taking the oil samples at 1/4-, 1/2-, 3/4-way stage. In order to avoid external contamination the MINIMESS transfer hose was pre-flushed with filtered oil carefully. However, an accumulation of particles on the oil side of the MINIMESS coupling cannot be ruled out. The oil samples at the beginning and at the end of the endurance test were carried out with a more extensive flushing of the sampling point.

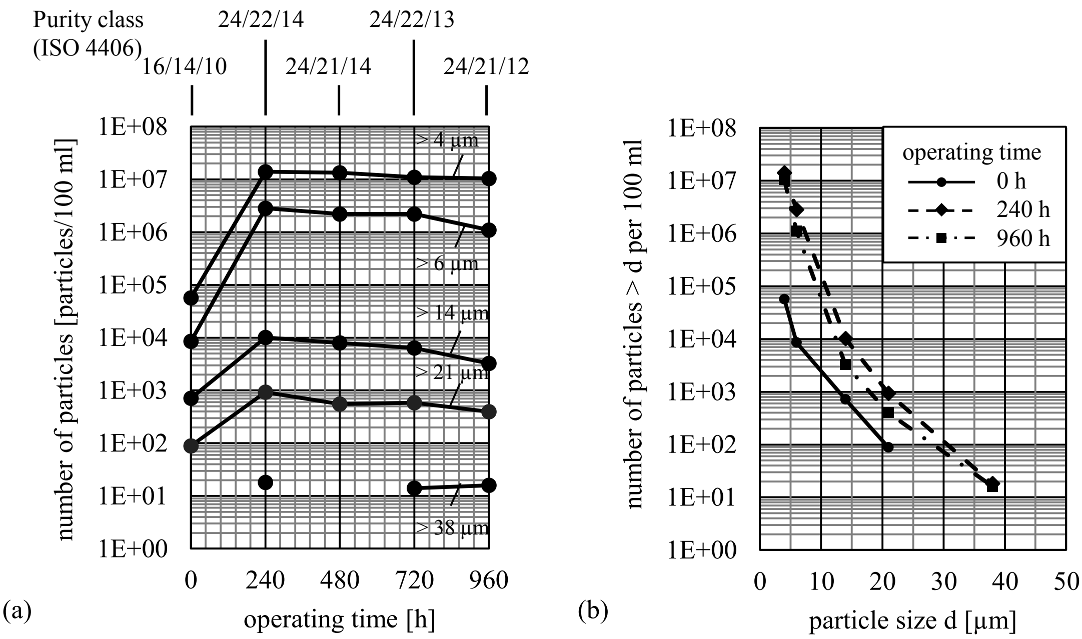


FIGURE 5. Particle number development during the endurance test: (a) as a function of time, (b) as a function of particle size

Finally, a visual inspection of the pump parts provides information on potential wear points and damages. As illustrated in **Figure 6**, the pumps consist of a gear stage in each case, comprising sprocket and ring gear. Four plain bearings support the radial forces, the ball bearing absorbs the axial forces. Potential wear points are marked in the figure.

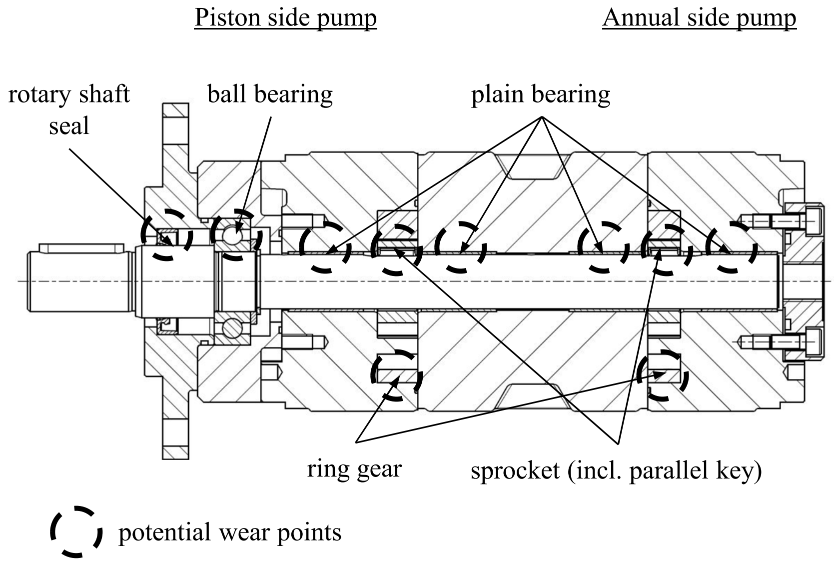
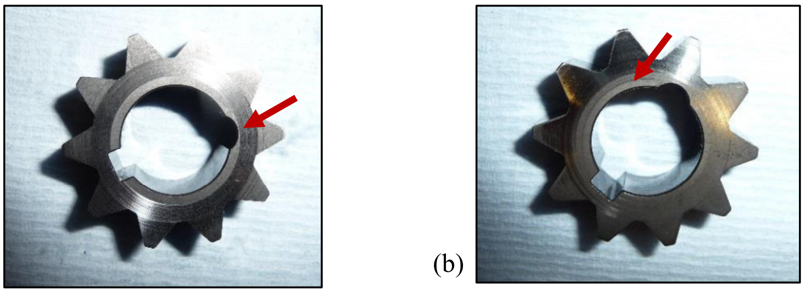


FIGURE 6. Potential wear points of the pumps

The visual inspection was conducted by the pump manufacturer. With exception of the sprockets all pump parts show ordinary run-in grooves. The sprockets exhibit more excessive run-in grooves on the face side, as can be seen in **Figure 7**. Since the sprockets are made of steel, this correlates with the increase of iron content in the oil, documented in Figure 4. According to the evaluation of the pump manufacturer the identified run-in grooves do not affect the proper operation of the pump. This demonstrates that although the particle concentration is significantly above the authorized limit of the pump manufacturer, the pump proved robust against the harsh conditions.



(a) (b)

FIGURE 7. Face side run-in grooves of the sprockets (a) piston side pump, (b) annual side pump

CONCLUSION AND OUTLOOK

Self-contained electrohydraulic compact drives can be found increasingly in industrial hydraulic applications. For conceptual reasons these drives contain only a very small oil volume, which is hermetically sealed. In order to save installation space and costs there are efforts to realize these drives without a filter. Under these conditions the wear behavior is not well known yet. This paper focuses on the investigation of self-contamination of electrohydraulic compact drives by means of endurance tests. The test procedure and the test-rig set up are introduced. The endurance test is executed by a compact drive demonstrator, which performs an industry-oriented load cycle. Periodically taken oil samples are used to document the contamination of the hydraulic circuit, the wear of the pumps is evaluated by means of a visual inspection. Results of a first test series are presented, in which the demonstrator is equipped with a standard pressure fluid HLP 46. The oil analysis shows a strong self-contamination of the circuit at the beginning of the test. In the further course of the experiment the number of particles measured via particle count remains almost constant, whereas the iron content measured via atomic emission spectroscopy is still increasing. The visual inspection of the pumps reveals that despite the high particle load the pumps proved robust against the harsh condition. All pump parts exhibit ordinary run-in grooves with exception of the sprockets. At these parts more excessive run-in grooves were documented, which do not affect the proper operation of the pumps though. However, due to the high particle load it can be concluded that an operation of an electrohydraulic compact drive without filter in combination with a standard hydraulic oil is not to be recommended.
In future works a systematic investigation of the wear and contamination behavior of electrohydraulic compact drives is targeted. This includes the investigation of different pump types and the influence of the pressure fluid on the wear behavior and self-contamination. It is expected to reduce abrasion and self-contamination by using a pressure fluid with higher load bearing capacity due to a better load bearing behavior in mixed friction areas. Moreover, the comparison of filtered and unfiltered circuits is focused to distinguish between ordinary run-in behavior and excessive wear caused by contamination. Considering the results shown in this paper it becomes clear that in particular in the beginning of the operation an excessive self-contamination occurs. Future experiments shall feature a particle sensor to be able to provide more detailed information on the chronological sequence of this process.
In a second key focus the process of dust infiltration via modern rod sealing systems should be targeted in order to clarify which dirt load has to be expected in different environments. All this knowledge together shall enable to evaluate, whether and under which conditions a design without filter is possible.

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